AC Loss Measurements for 2G HTS Racetrack Coils With Heat-Shrink Tube Insulation

Min Zhang, W. Wang, Z. Huang, M. Baghdadi, W. Yuan, J. Kvitkovic, S. Pamidi, and T. A. Coombs

***Abstract*—A heat-shrink tube insulation for second-generation high-temperature superconducting (2G HTS) coils is studied experimentally in this paper. The insulation can be used to prevent the delamination of 2G HTS due to epoxy impregnation. According to the experiment results, the insulated coil shows no degradation before and after the epoxy impregnation. To validate the performance of 2G HTS coils with the heat-shrink insulation, we measured the transport loss, magnetization loss and total loss of a 2G HTS coil. The study demonstrates the feasibility of the heat-shrink tube insulation method for electrical applications.**

***Index Terms*—AC loss, delamination, HTS, racetrack, YBCO.**

I. Introduction

KAPTON TAPES are widely used for providing insulation for second-generation high-temperature superconducting (2G HTS) tapes [1]. One disadvantage of using kapton tape as insulation is that the helical winding technique results in the uneven surface of 2G HTS tape. During the epoxy impregnation process, epoxy will penetrate into the HTS tape by the gaps between the Kapton tapes. It is desirable to impregnate the HTS coil with epoxy resin to prevent wire movement and fatigue. However, epoxy has different thermal expansion coefficient in comparison with HTS tapes. Epoxy resin typically contracts 5 or 6 times more than a metal when the temperature is 30 K [2]. During the cooling down process, the shrink of epoxy causes a transverse stress on the metal surface of HTS, and also cleavage stresses at edge of wire. Although HTS tapes can stand more than 500 MPa stress in longitudinal directions, the transverse stress is as low as 10 MPa [3], and the nominal cleavage strength for the slit edge of the YBCO coated conductor is extremely low typically being 0.5 MPa [4]. High transverse stress leads to the delamination of HTS tapes, as reported in [3], [4], which means that the stabilizer and YBCO on substrate layers are separated. The delamination of HTS tapes results in the decreasing of critical current density and degradation of HTS coils [3].

To prevent the influence of epoxy, it is preferable to keep it away from the HTS tapes. Paper [5] introduced a polyimide-electrodeposited YBCO-coated conductor in order to prevent tape degradation. Also wax and commercial enamel were proposed to replace epoxy [6]. The insulation material introduced in this paper is the so-called heat-shrink tube, which is made of polyester [7]. The insulation method was first proposed for the application of high field magnets, and the authors successfully demonstrated that the insulation can prevent HTS tape delamination at 35.4 T [8]. In this paper, we demonstrate that the insulation technique can prevent tape degradation, and can be applied to electrical power applications.

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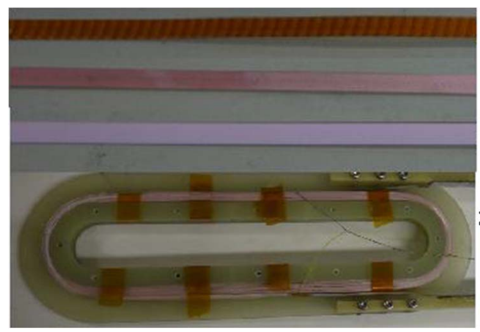

Fig. 1. 2G HTS racetrack coil with the heat-shrink tube insulation.

II. The Heat-Shrink Tube Insulation Technique

Fig. 1 illustrates the comparison between a piece of 2G HTS tape with the heat-shrink tubing insulation and a piece of 2G HTS tape with kapton insulation. By inserting the YBCO tape into the heat-shrink tube, and evenly heating it up to 300 F for a few seconds, the tube will shrink and firmly attach to the YBCO tape. For the connection between two tubes, around 10 cm overlapping is allowed to prevent YBCO getting contact with epoxy. The heat-shrink tube insulation provides a smooth surface for 2G HTS tapes, and it forms no gap between the insulation and HTS for epoxy to penetrate. The tubing material works perfectly in the temperature of liquid nitrogen, and no degradation of the insulation itself has been observed during and after the cooling down.

Table I is the parameters of the new racetrack coil we made using the insulated 2G HTS tape (as shown in Fig. 1). The double racetrack coil was wound with no tension on a G10 former. Another racetrack coil with Kapton insulation and the same geometry was wound and tested, with AC loss measurements published in Paper [9].

In order to prove the function of the heat-shrink tube insulation, we performed an experimentally comparison. We wound a racetrack coil with the heat-shrink tube insulation on 2G HTS

TABLE I
DOUBLE RACETRACK PARAMETERS

Quantity	Value
Turns per layer N	38
Total tape length L	39.5m
Tape width	4 mm
Coil critical current	39.5 A (77 K)
Average thickness per turn	0.25 mm
Former outer width	50 mm
Former outer length	230 mm

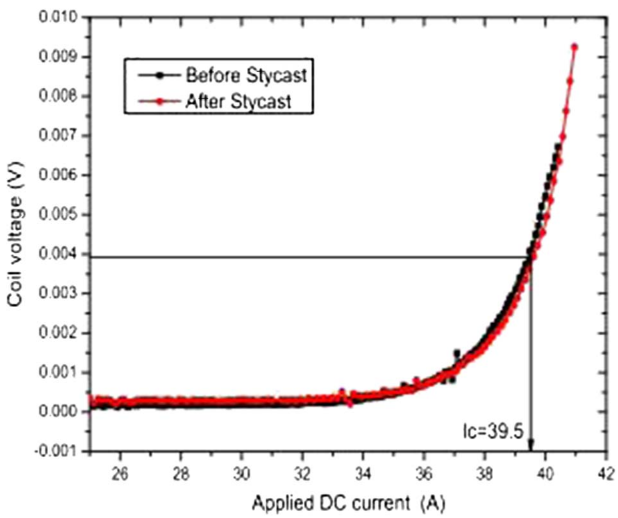

Fig. 2. I–V curves of the racetrack coil before and after Stycast impregnation.

tapes, and measured its I–V curve. Then epoxy impregnation was applied (Stycast) to the coil, and its I–V curve was measured again after impregnation. Fig. 2 shows the comparison results. The I–V curves before and after the impregnation are almost identical, which proves that the performance of 2G HTS coil is not affected by the epoxy impregnation, owning to the protection from the insulation. Applying the 100 μV/m criterion, the critical current of the racetrack coil is determined as 39.5 A. The measurement proves that the new insulation technique can effectively prevent HTS degradation due to the epoxy impregnation.

III. AC Loss Measurement

To evaluate the coil performance, we performed several AC loss tests for the racetrack coil, including transport loss measurement using electrical method, magnetization loss and total loss measurement using calorimetric method.

Transport Loss Measurement: The details about the experimental setup of electrical method can be found in paper [9], and it is the same method used in the AC loss measurement in paper [10], [11]. In principle, we measure the in-phase voltage V and current I of the coil (both are rms value) and use (1) to calculate transport loss (J/cycle):

$$Q = VI/f \tag{1}$$

where f is the frequency of applied current.

The transport loss for various frequencies was measured, with the results shown in Fig. 3. These are concerns that the

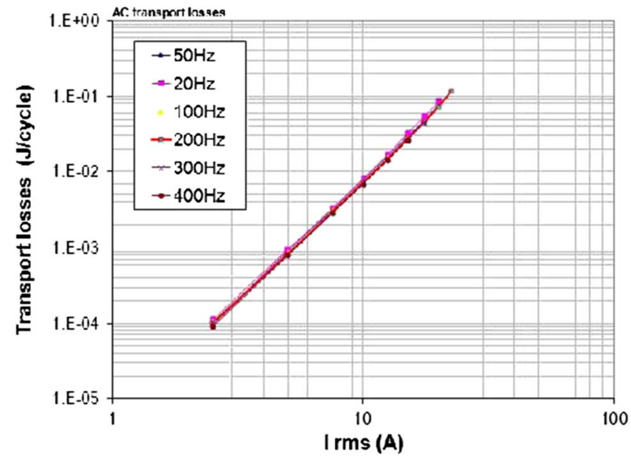

Fig. 3. Transport loss measured by the electrical method.

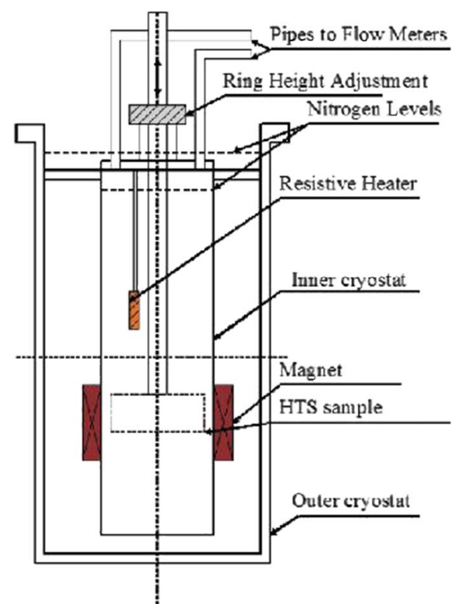

Fig. 4. Experimental setup for the calorimetric method.

cooling for the HTS tapes with the new insulation is not as good as the ones with Kapton tape, because the HTS tapes are fully covered with the insulation. To address this issue, the racetrack coil was tested up to 400 Hz. As shown in Fig. 3, there is no obvious difference between the AC loss of low frequencies and high frequencies, suggesting that the temperature inside the coil was not phenomenal enough to affect the AC loss value.

Magnetization Loss Measurement: Alternative external field induces the shielding current inside HTS, leading to magnetization loss of the racetrack coil. We used calorimetric method to measure the magnetization loss. The heat generated by the racetrack coil can boil off the surrounding liquid nitrogen. By measuring the flow rate of the nitrogen gas F, we can deduce the loss of the racetrack coil. Fig. 4 shows the experimental setup for the measurements.

The magnet generates an external field for HTS coil. Two pipes are connected to the flow meters to avoid local pressure accumulation. The sum of the readings from two flow meters gives the total flow rate corresponding to a loss value. A resistive heater is used to calibrate the nitrogen flow rate. We

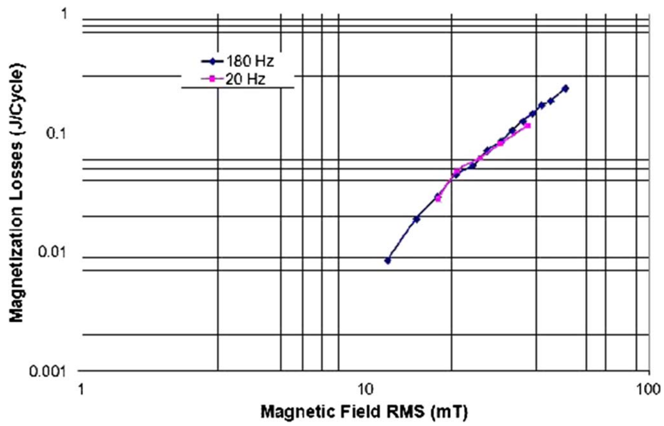

Fig. 5. Magnetization loss measured by the calorimetric method.

draw the flow rate F versus resistive heater power curve, and the ratio of the curve is corresponding to the flow rate constant N [(L/min)/W]. The magnetization loss (J/cycle) can be calculated by (2):

$$Q = F/Nf \tag{2}$$

where f is the frequency of applied field.

Fig. 5 shows the results of magnetization loss with two frequencies. The magnetic field is in the perpendicular direction to the tape surface in the straight racetrack region.

Total Loss Measurement: The advantage of the calorimetric method over the electrical method is that it can measure the total loss of HTS regardless of the phase difference between applied current and background field. However, the sensitivity of the calorimetric method is not as good as that of electrical method. In our setup, any loss lower than 0.5 W is impossible to measure accurately, due to the sensitivity of the flow meters. The fluctuation of background flow is usually up to 0.1 L or more. It is therefore more accurate to measure AC losses at relative higher frequencies.

We also used the calorimetric method to measure the total loss of the racetrack coil while it is carrying a transport current and subjected to an external magnetic field. The loss dissipation from the current leads needs to be subtracted from the total flow. So we performed a measurement without the HTS racetrack coil, and recorded the flow rate in order to identify the contribution from the current leads. The results show (see Fig. 6) that when the applied current is low (< 10 A), the contribution of AC loss is dominated by magnetization loss. Because the total losses of 5 A and 10 A are similar, and they are also similar to the AC loss without applied current as shown in Fig. 5. By contrary, the applied current 15 A greatly increases the total loss of the racetrack coil.

IV. Discussion

To validate the performance of the HTS coil with the heat-shrink tube insulation, we compare the transport loss of it with the transport loss of a HTS racetrack coil with Kapton insulation [12]. The two coils have the same geometry. Fig. 7 shows the comparison of transport loss for two racetrack coils. The measurements show that the two insulation techniques lead

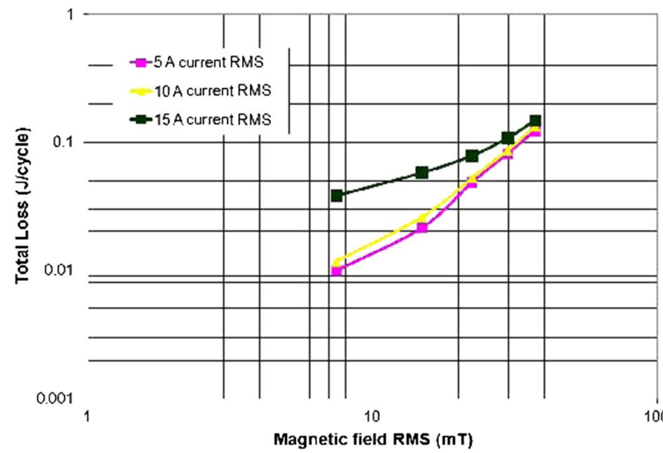

Fig. 6. Total loss measured by the calorimetric method.

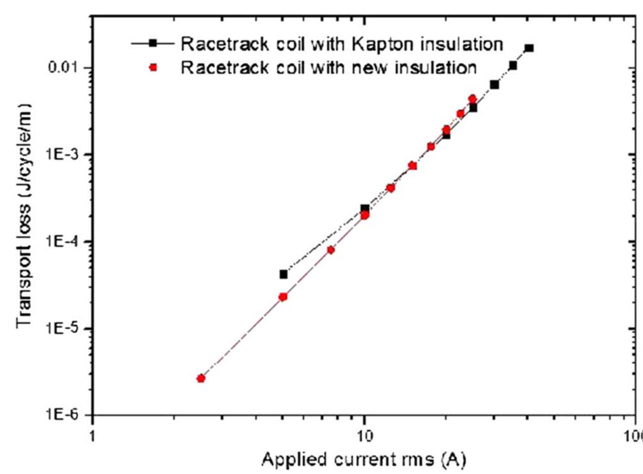

Fig. 7. Transport loss comparison of a HTS coil with the heat-shrink tube insulation and a HTS coil with Kapton insulation.

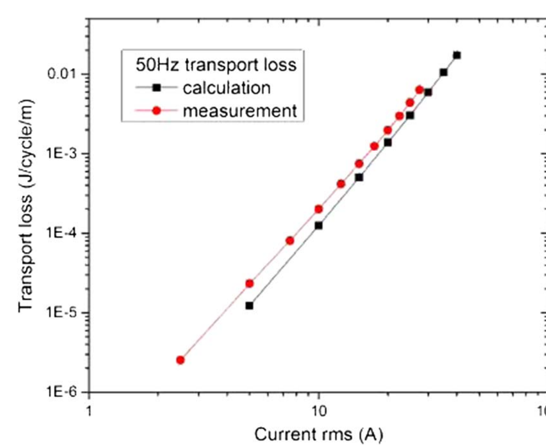

Fig. 8. Transport loss comparison between measurements and calculations of the HTS coil with the heat-shrink tube insulation.

to similar amount of AC loss (J/cycle/m). It proves the feasibility of the heat-shrink tube insulation, because no additional loss is observed by using this technology.

To further validate the AC loss measurement, finite element model was employed to calculate the AC loss. The finite element model for a double racetrack HTS coil was introduced in detail in paper [12]. Fig. 8 shows the results. Calculation results are slightly lower than real measurements, due to the geometry discrepancy between the model and the coil [12].

V. Conclusion

In order to prevent the degradation of HTS tapes due to epoxy impregnation, we introduced a heat-shrink tube technique as the insulation for HTS tapes. The insulation separates HTS tapes from epoxy completely, and the experiments showed no degradation of the testing coil after the epoxy impregnation. In order to prove the feasibility of the insulation for electrical applications, we measured the AC losses of a racetrack coil under transport current and applied field conditions. The results showed no obvious heating of the coil: different insulated coils give roughly the same amount of transport current losses in the same transport current range.

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